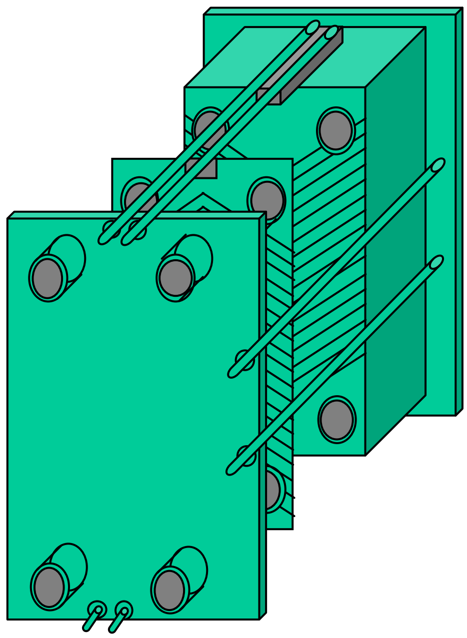
INSTED PLATE FRAME HEAT EXCHANGER SAMPLE PROBLEM AND VALIDATION DOCUMENTATION



June 2003

About INSTED's Sample Validation Problems

INSTED sample problems are selected to rigorously test the calculations of the INSTED thermal analysis workbench and heat exchanger programs. Some of the problems are standard industry benchmark problems, while others were developed based on physical calculations on heat exchangers in conjunction with heat exchanger manufacturers and INSTED customers.

The sample problems also serve as a starting point for many INSTED users who load sample problems similar to their own problems and simply modify the input as required.

Running a Sample Problem

To run the sample problem contained in the project file *'prob1.inp*', for instance, follow these procedures:

1. Click 'Project Admin' on the Main dialog box.
2. Click the "Load Project" button.
3. Go to the subdirectory 'samples' by double-clicking on the 'samples' folder.
4. Type " *.* " in the filename position and press Enter.

→ A list of the files present in the directory is displayed.

5. Select the file *'prob1.inp*' and click on the 'Open' button.
6. Close the 'Project Admin' dialog by clicking its 'Ok' button.
7. Click 'Compute' on the Main dialog and wait for computation to end.

→ The results of the calculations are displayed in the Main dialog box.

8. Click 'Print Results' to receive a specification sheet of the results.
9. On the top left corner of the screen, select File/Print, to obtain a hard copy of the specification sheet results.
10. Click any point on the specification sheet to exit the sheet and return to the analysis environment.

Problem 1
Single Phase Problem

A plate heat exchanger has 99 plates, each 1 m high and 0.25 m wide, with a gap between them of 5 mm. The plates have the heat transfer and pressure drop characteristics similar to those of a 30° chevron plate. Cold water initially at 15°C is fed into the heat exchanger at a rate of 5 kg/s and flows through half the passages in countercurrent flow to hot water, initially at 95°C flowing at 10 kg/s. The properties of the warm and cold stream are as shown in the table below. What is the exit temperature of the cold stream? What would be the effect of reducing the number of plates (neglecting end effects)?

	Warm Stream	**Cold Stream**
Density (kg/m^3)	985.2	985.2
Specific heat (J/kgK)	4183	4183
Viscosity (kg/ms)	0.000505	0.000505
Fluid thermal conductivity (W/mK)	0.648	0.648

Source

Hewitt, G. F., Shires, G. L., Bott, T. R. Process Heat Transfer, CRC Press. 1998. Pages 321-323.

Comparisons

	Source	**INSTED**	**Difference**
Velocity (w) m/s	0.162	0.162	0
Velocity (c) m/s			
Reynolds No. (w)	3.16 x 10^3	3.168 x 10^3	< 1%
Reynolds No. (c)			
Heat Transfer Coefficient (w) W/(m^{2}K)	7.19 x 10^3	7.037 x 10^3	2%
Heat Transfer Coefficient (c) W/(m^{2}K)	4.61 x 10^3	4.81 x 10^3	4%
U W/(m^{2}K)	2.81	2.857	1.6%
NTU	3.33	3.415	2.5%
Effectiveness	0.896	0.900	< 1%
$T_{c,out}$ (K)	359.86	360.194	< 1%

Effect of Number of Plates

N	**NTU$_{min}$**		**Effectiveness**		**$T_{c,out}$ (°C)**	
	Source	INSTED	Source	INSTED	Source	INSTED
100	3.33	3.4152	0.896	0.900	86.7	87.0
76	3.01	3.0228	0.875	0.876	85.0	85.1
50	2.57	2.5419	0.839	0.836	82.1	82.0
26	1.99	1.9965	0.773	0.774	76.8	76.9

INSTED Project files: prob1.pfr.

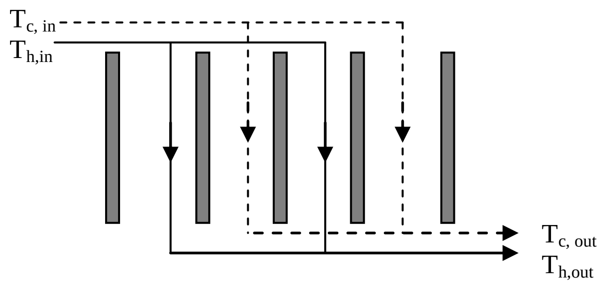
Effect of Multiple Passes

The above heat exchanger configuration was used to validate multi-pass exchangers using the formula in heat exchangers (get reference).
In the formula below, R is the heat capacity ratio, NTU is the number of thermal units, and P is the temperature effectiveness

1-pass by 1-pass parallel flow plate exchanger (N = 100)

$$P_{source} = \frac{1 - e^{[-NTU(1+R)]}}{1+R}$$

$$P_{N\to\infty} = \frac{1}{1+R}$$



<u>INSTED CALCULATION</u>

$T_{c,o}$ = 341.18K
NTU = 3.4152
□ = 0.6628
P = (341.18 - 288.16)/(368.16 - 288.16) = **0.66275**

<u>SOURCE</u>

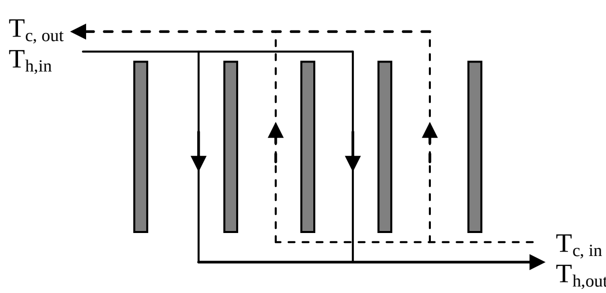
P = 0.994/1.5 = **0.66269**

$P_{N\to\infty}$ = 1/1.5 = 0.6667

1-pass by 1-pass counter flow plate exchanger (N = 100)

$$P_{source} = \frac{1 - e^{[-NTU(1-R)]}}{1 - \mathrm{Re}^{[-NTU(1-R)]}}$$

$$P_{N\to\infty} = 1$$



<u>INSTED CALCULATION</u>

$T_{c,o}$ = 360.19K
NTU = 3.4152
□ = 0.9003
P = (360.19 - 288.16)/(368.16 - 288.16) = **0.90037**

<u>SOURCE</u>

P = 0.8187/0.9093 = **0.900313**

$P_{N\to\infty}$ = 1

The plots of the temperature and heat flux through the exchanger for both configurations are shown below. The figure shows expected thermal analysis profiles for parallel and counter current flow heat exchanger arrangements, respectively. For instance, for the parallel flow configuration, both streams asymptotically approach the same temperature as they flow through the exchanger, and at no point will the temperature of the cold stream be greater than that of the hot stream. Also, the heat flux is initially high at the entrance to the exchanger, where the temperature difference is maximum and drops as the temperature difference reduces as the hot stream becomes cooler and the cold stream becomes warmer. The INSTED procedure duplicates the physics of the problem since it uses a detailed, discrete procedure to compute the thermal characteristic of both streams as they pass through the exchanger.

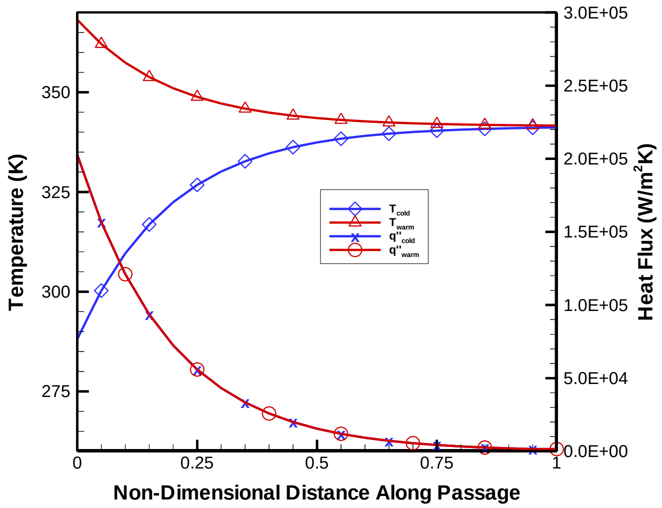


Figure 1. Stream Temperature and Heat Flux Through the 1-pass by 1-pass Exchanger (Parallel Flow Arrangement)

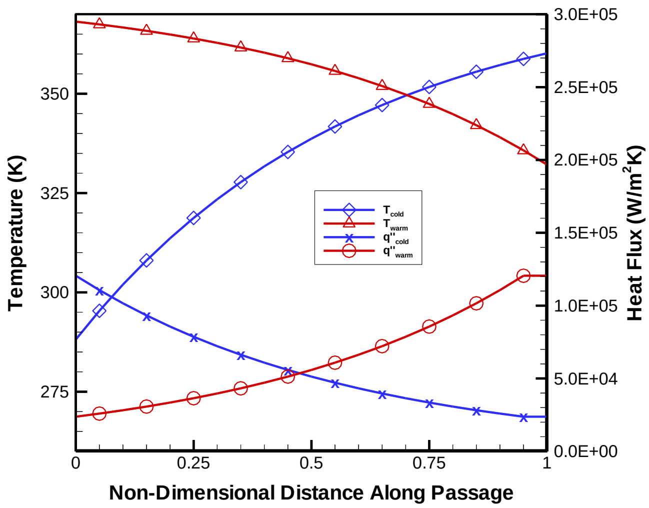


Figure 2. Stream Temperature and Heat Flux Through the 1-pass by 1-pass Exchanger (Counter Flow Arrangement)

INSTED Project files: prob1.pfr

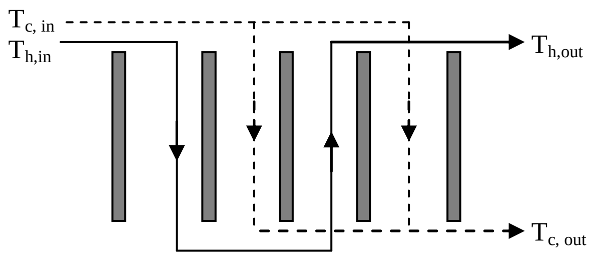
2-pass by 1-pass (parallel/counter) flow plate exchanger (N = 200)

$$A = P_p(NTU, R/2)$$

$$B = P_C(NTU, R/2)$$

$$P_{source} = \frac{1}{2}\left[A + B - RAB/2\right]$$

$$P_{N\to\infty} = \frac{2}{2+R}$$



INSTED CALCULATION

$T_{c,o}$ = 351.76 K
NTU = 5.5107
□ = 0.79495
P = (351.76 - 288.16)/(368.16 - 288.16) = **0.795**

SOURCE

P_P = 0.799
P_C = 0.988
P = 1/2 (0.799 + 0.988 - 0.5*0.799*0.988/2) = **0.795**

$P_{N\to\infty}$ = 2/2.5 = 0.8

The plots of the temperature and heat flux through the exchanger for both configurations are shown below. The profiles of the warm stream temperature and heat flux show characteristics of a stream undergoing first parallel, then counter flow heat exchange with a cooler stream.

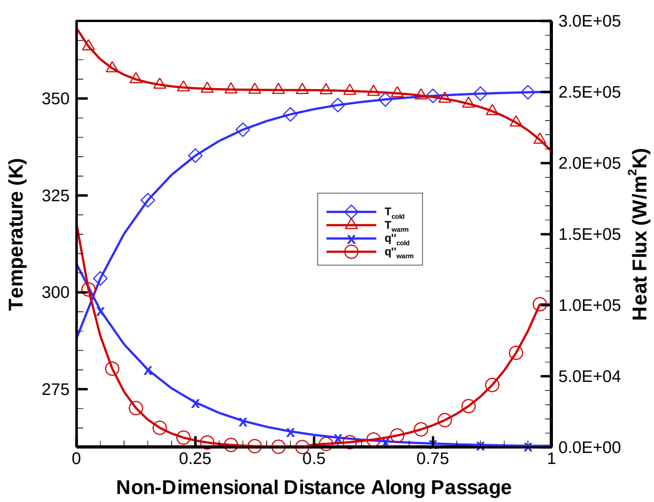


Figure 3. Stream Temperature and Heat Flux Through the 2-pass by 1-pass Exchanger (Parallel/Counter Flow Arrangement)

INSTED Project files: prob2.pfr

3-pass by 1-pass (parallel/counter/parallel) flow plate exchanger (N = 300)

$$P_{N\to\infty} = \frac{9+R}{(3+R)^2}$$

<u>INSTED CALCULATION</u>

$T_{c,o}$ = 350.16 K
NTU = 7.2855, □ = 0.77499
P = (350.16 - 288.16)/(368.16 - 288.16) = **0.77499**

<u>SOURCE</u>

$P_{N\to\infty}$ =9.5/3.5^2 = **0.7755**

3-pass by 1-pass (parallel/counter/parallel) flow plate exchanger (N = 300)

$$P_{N\to\infty} = \frac{9-R}{9+3R}$$

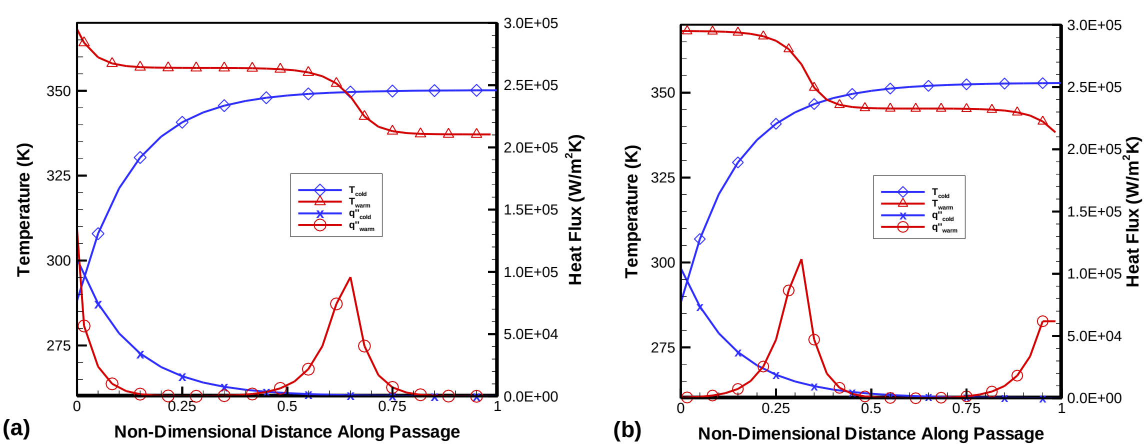
<u>INSTED CALCULATION</u>

$T_{c,o}$ = 352.83 K
NTU = 7.2855, □ = 0.8086
P = (352.83 - 288.16)/(368.16 - 288.16) = **0.8086**

<u>SOURCE</u>

$P_{N\to\infty}$ =8.5/10.5 = **0.8095**

The values temperature and heat flux for both streams though the exchanger, shown below, also show characteristics consistent with parallel/counter/parallel flow for the first case, and counter/parallel/counter flow for the second case.

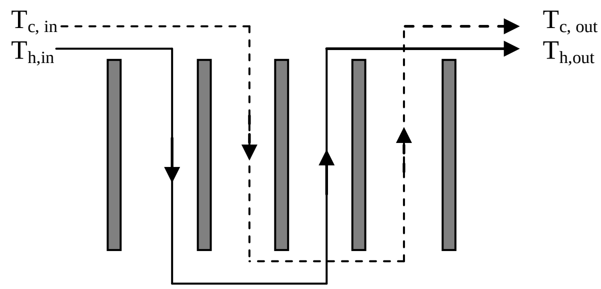


<u>Figure 4. Stream Temperature and Heat Flux Through the 3-pass by 1-pass Exchanger (a) Overall Parallel Arrangement (b) Overall Counter Flow Arrangement</u>

INSTED Project files: prob3.pfr

2-pass by 2-pass parallel flow plate exchanger (N = 100)

$$P_{N \to \infty} = \frac{1}{1+R}$$



<u>INSTED CALCULATION</u>

$T_{c,o}$ = 341.49K
NTU = 6.8304
□ = 0.666625
P = (341.49 - 288.16)/(368.16 - 288.16) = **0.666625**

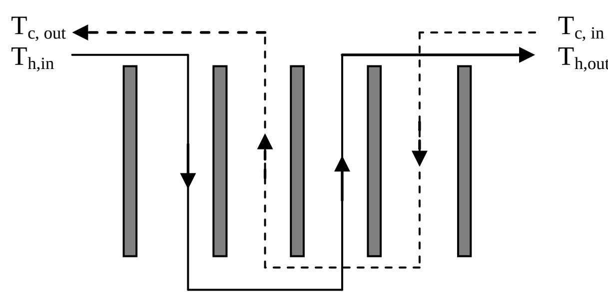
<u>SOURCE</u>

$P_{N\to\infty}$ = 1/1.5 = 0.6667

2-pass by 2-pass counter flow plate exchanger (N = 100)

$$B = P_C(NTU/2, R)$$
$$P_{source} = B\left[2 - B(1+R)\right]$$

$$P_{N \to \infty} = 1 - R$$



<u>INSTED CALCULATION</u>

$T_{c,o}$ = 334.94K
NTU = 6.8304
□ = 0.5847
P = (334.94 - 288.16)/(368.16 - 288.16) = **0.58475**

<u>SOURCE</u>

P_C = 0.81868/0.90934 = 0.9003
P = 0.9003{2 - 0.9003(1 + 0.5)} = **0.58479**

$P_{N\to\infty}$ = 0.5

INSTED Project files: prob4.pfr

3-pass by 2-pass (overall parallel) flow plate exchanger (N = 120)

$$P_{N \to \infty} = \frac{9 - 2R}{9 + 6R}$$

<u>INSTED CALCULATION</u>

$T_{c,o}$ = 341.94 K
NTU = 8.1345
□ = 0.672
P = (341.94 - 288.16)/(368.16 - 288.16) = **0.672**

<u>SOURCE</u>

$P_{N \to \infty}$ =7/10 = **0.700**

3-pass by 2-pass (overall counter-current) flow plate exchanger (N = 120)

$$P_{N \to \infty} = \frac{27 + 12R - 4R^2}{27 + 12R - 4R^2}$$

<u>INSTED CALCULATION</u>

$T_{c,o}$ = 341.94 K
NTU = 8.1345
□ = 0.672
P = (341.94 - 288.16)/(368.16 - 288.16) = **0.672**

<u>SOURCE</u>

$P_{N \to \infty}$ =(27+6-1)/(27+6+1) = **0.9411**

4-pass by 2-pass (overall parallel) flow plate exchanger (N = 160)

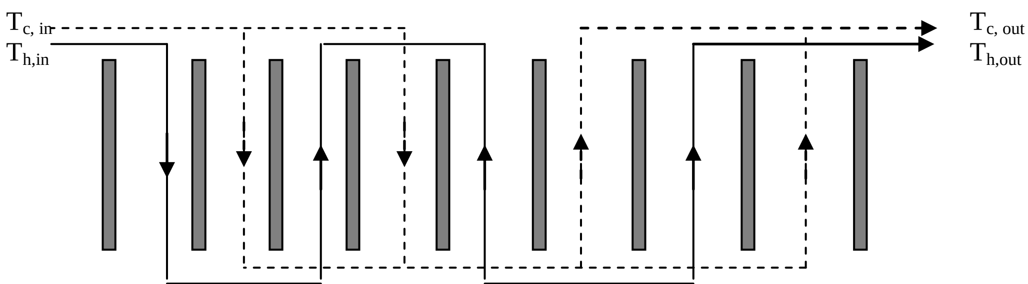
$$P_{N\to\infty} = \frac{4}{(2+R)^2}$$

<u>INSTED CALCULATION</u>

$T_{c,o}$ = 339.61 K
NTU = 9.879
□ = 0.643
P = (339.61 - 288.16)/(368.16 - 288.16) = **0.643**

<u>SOURCE</u>

$P_{N\to\infty}$ =4/6.25 = **0.640**



4-pass by 2-pass (overall counter-current) flow plate exchanger (N = 160)

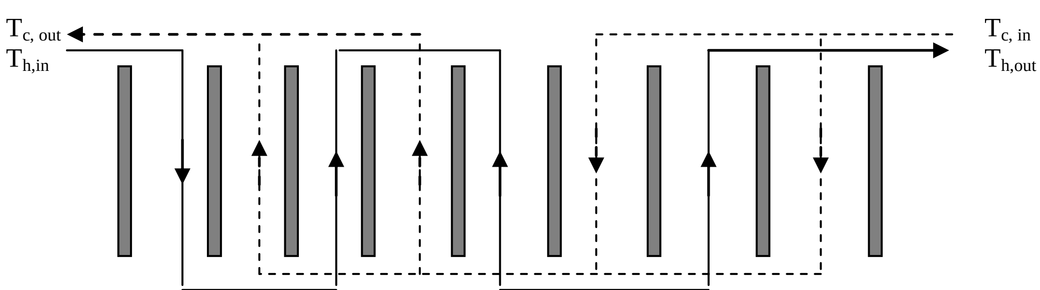
$$P_{N\to\infty} = \frac{4}{4+R^2}$$

<u>INSTED CALCULATION</u>

$T_{c,o}$ = 339.61 K
NTU = 9.879
□ = 0.643
P = (339.61 - 288.16)/(368.16 - 288.16) = **0.643**

<u>SOURCE</u>

$P_{N\to\infty}$ = 4/4.25 = **0.9411**



Problem 2
Sample Boiling Problem

A plate heat exchanger 40 plates each 1m x 0.25m with a gap of 5 mm is used to cool a hot fluid initially at 95°C flowing at 4 kg/s. The cooling fluid is R134a at -10°C flowing at 20kg/s with a quality of 0.381. The plates have the heat transfer and pressure drop characteristics similar to those of a 30° chevron plate.
Calculate the outlet temperature and quality of the cold stream as well as the outlet temperature of the hot fluid.
Properties of the hot fluid are as shown in the table below.
Properties of R134a were obtained from the INSTED database at the varying temperatures of the refrigerant as it passes through the exchanger.
What would be the effect of reducing the flow rate of the refrigerant to 12 kg/s

Density (kg/m^3)	985.2
Specific heat (J/kgK)	4183
Viscosity (kg/ms)	0.000505
Fluid thermal conductivity (W/mK)	0.648

Results

	Cold Stream Flow Rate (kg/s)	
	20	**12**
$T_{h,out}$ (°C)	-8.21	-0.13
$T_{c,out}$ (°C)	-10	-3.34
$x_{c,out}$	0.797	1.000
Q (W)	1.73×10^6	1.59×10^6

The result of reducing the cold stream flow rate to 12 kg/s is to cause the complete boil off and super-heating of the refrigerant by the point it exits the exchanger.

The graph below shows the plot of the temperature and quality of both streams as they flow through the exchanger.

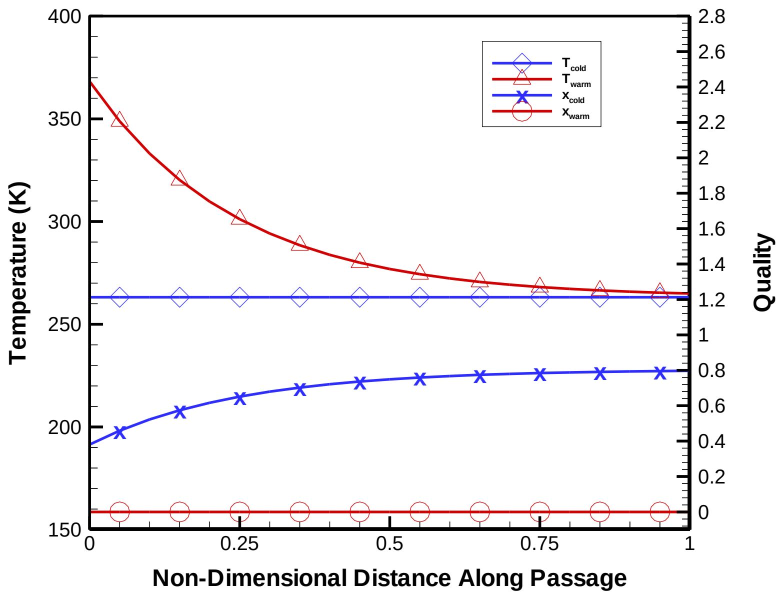


Figure 3. Stream Temperature and Quality Through the Exchanger
(Cold Stream Flow Rate = 20 kg/s)

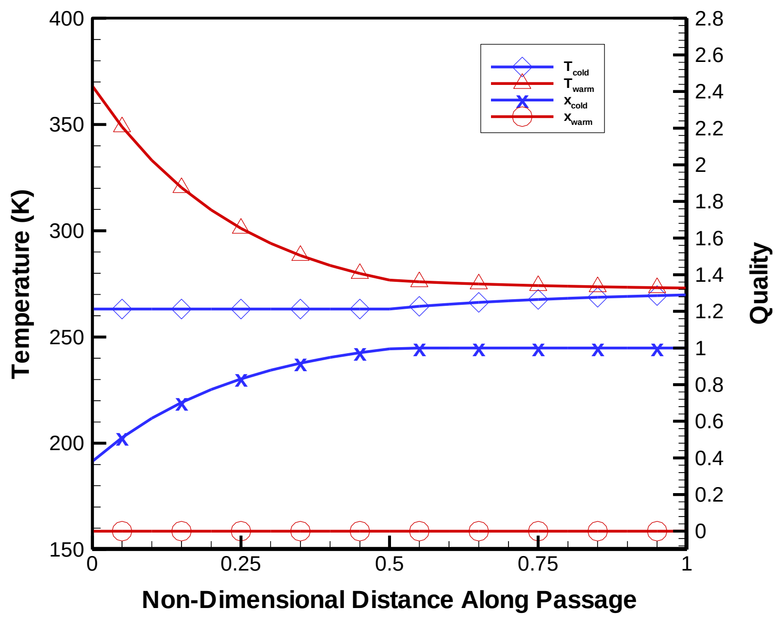


Figure 4. Stream Temperature and Quality Through the Exchanger
(Cold Stream Flow Rate = 12 kg/s)

INSTED Project files: prob5.pfr, prob6.pfr

Problem 3
Sample Condensation Problem

Consider the same plate frame heat exchanger as in Problem 2 being used to cool steam at 117°C. The flow rates of the hot and cold streams are respectively 0.1 and 1 kg/s. The inlet temperature of the cold stream was initially at -23°C. Calculate the outlet temperature and quality of the steam as it exits the exchanger. Also determine the outlet temperature of the cooling stream.

If the flow rate of the cold stream was increased to 2 kg/s, what effect would this have on the condensing stream?

The properties of the cold stream are as shown in the table below.
Properties of steam were obtained from the INSTED database at the varying temperatures of the hot stream as it passes through the exchanger.

Density (kg/m^3)	822.78
Specific heat (J/kgK)	1088.93
Viscosity (kg/ms)	0.0002047
Fluid thermal conductivity (W/mK)	0.06487

Results

	Cold Stream Flow Rate (kg/s)	
	1	**2**
$T_{c,out}$ (°C)	99.08	81.96
$T_{h,out}$ (°C)	100.0	81.97
$X_{h,out}$	0.4108	0.0
Q (W)	1.39 x 10^5	2.40 x 10^5

The result of increasing the cold stream flow rate to 2 kg/s is to cause the complete condensation and sub-cooling of the steam by the point it exits the exchanger.

The graph below shows the plot of the temperature and quality of both streams as they flow through the exchanger.

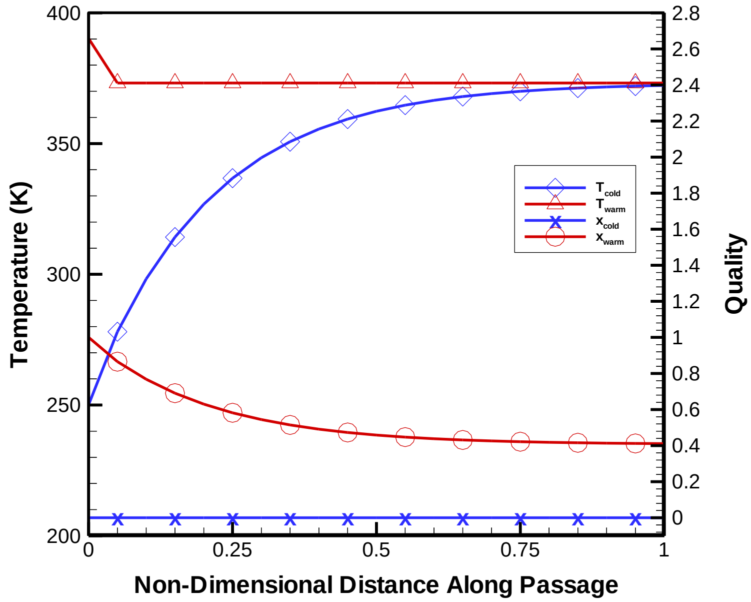


Figure 5. Stream Temperature and Quality Through the Exchanger (Hot Stream Flow Rate = 1 kg/s)

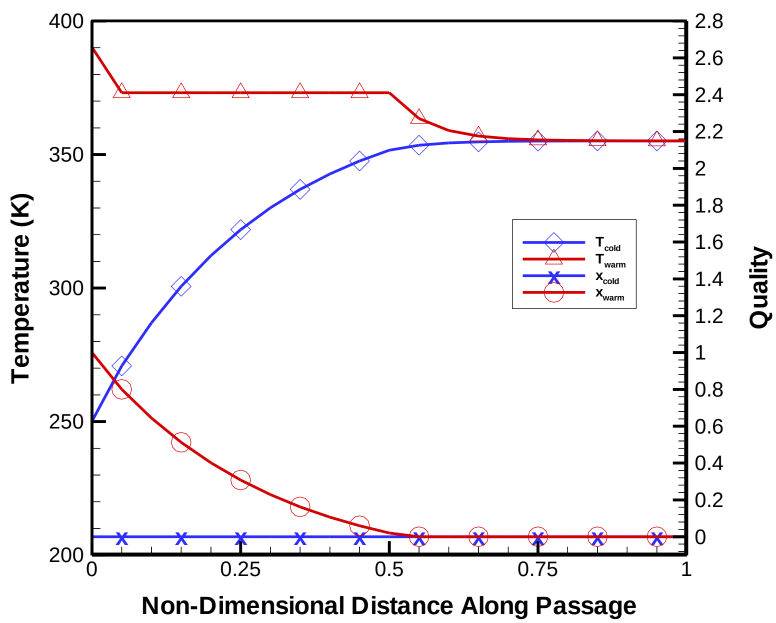


Figure 6. Stream Temperature and Quality Through the Exchanger (Hot Stream Flow Rate = 2 kg/s)

INSTED Project files: prob7.pfr, prob8.pfr